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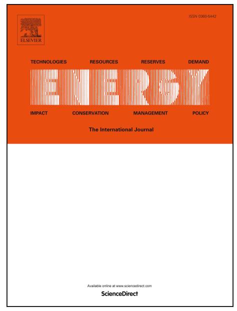

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Abstract:

One of the prospective technologies that can be used for energy generation in distributed systems is based on biogas production, usually involving fermentation of various types of biomass and waste. This article aims to bring novelty on the analysis of this type of systems, joining together thermodynamic, economic and environmental aspects for a cross-cutting evaluation of the proposed solutions. The analysis is made for Spain, for which such a solution is very promising due to availability of the feedstock. A detailed simulation model of the proposed system in two different cases was built in Aspen Plus software and Visual Basic for Applications. Case 1 involves production of biogas in manure fermentation process, its upgrading (cleaning and removal of CO_2 from the gas) and injection to the grid. Case 2 assumes combustion of the biogas in gas engine to produce electricity and heat that can be used locally and/or sold to the grid. Thermodynamic assessment of these two cases was made to determine the most important parameters and evaluation indices. The results served as input values for the economic analysis and environmental evaluation through Life Cycle Assessment of the energy systems. The results show that the analysed technologies have potential to produce high-value products based on low-quality biomass. Economic evaluation determined the break-even price of biomethane (Case 1) and electricity (Case 2), which for the nominal assumptions reach the values of 16.77 €/GJ and 28.92 €/GJ, respectively. In terms of environmental assessment the system with the use of biogas in gas engine presents around three times better environmental profile than Case 1 in the two categories evaluated, i.e., carbon and energy footprint.

Keywords:

Biogas; thermodynamic analysis; economic analysis; life cycle assessment; manure fermentation, biogas upgrading.

1. Introduction

In recent years an increasing interest is observed in the use of gases from anaerobic digestion which are included in the group of biogases, i.e., gases resulting from the activity of methanogenic anaerobic bacteria, causing the decomposition of organic matter (in the process called methane fermentation or methanogenesis) [1,2]. The main components of biogas are methane and carbon dioxide. The lower heating value of biogas is usually around 20 MJ/Nm^3. The main sources of biogases are wastewater treatment plants, landfills and agricultural and municipal biogas plants. The main advantage of these gases is that their main combustible component is methane (making it an easy fuel for combustion in, e.g., gas engines and gas turbines) and that there are many ways for their generation as well as upgrading to the quality of natural gas [3-9]. From the environmental point of view, the use of these gases for energy purposes is recommended rather than releasing them to the atmosphere, thereby contributing to a decrease in the use of fossil fuels.

Biogas generation has become an important branch of distributed energy generation in many European countries. Its production in the European Union (EU) reached 654 PJ in 2015 (which is the equivalent of more than 18 billion m^3 of natural gas) and increased 7 times since the year 2000 [10]. The highest production of biogas in 2015 was in Germany and was equal to 328,840 TJ (9160 million m^3), meaning 12.1% of biogas share in natural gas use, which is high compared to other EU countries (apart from Sweden, with a share of 23.2%). Significant production is also observed in the UK (94,303 TJ) and Italy (78,355 TJ), however, with a share in natural gas use at only 3.7% and 3.4%, respectively [10]. A significant use of biogas was also observed in the Czech Republic (9.5%), Latvia (8.0%), Denmark (5.3%), Finland (4.6%), Slovenia (4.5%) and Austria (4.4%), with the average in the EU at 4.4%. In 2015 in Spain 10,954 TJ (305 million m^3) of biogas were produced, which with the consumption of 28,538 million m^3 of natural gas makes up 1.1% of share of biogas. Most of biogas in Spain comes from landfill gas recovery and sewage plants [10].

According to the European Biogas Association [11], in 2018 there were 18,202 biogas plants and 610 biomethane plants in Europe (compared to 17,662 and 497, respectively, in 2016). Thus, a significant increase, especially in terms of biomethane production, is observed. In the same time, more than 1.4 billion cubic meters of biomethane were injected to the grid.

Although there is a considerable amount of data concerning yields and composition of biogas coming from anaerobic digestion, the values presented in the literature are in a very wide range (e.g., [12-17). This is closely linked to the number of different sources (types and composition) of biomass that can be used, which also affects the environmental performance of biogas productions systems [18]. Usually the biogas yield is in the range from around 20 m^3/tonne fresh matter to 400 m^3/tonne fresh matter and even more, up to over 1000 m^3/tonne fresh matter [12,15]. Properly conducted methane fermentation can lead to biogas with up to 85% of CH_4, with the average methane content being 65% and the remaining part being CO_2. Therefore, in addition to the fact that biogas production is a way to utilise various types of organic waste, it is also a process of obtaining a relatively valuable gaseous fuel. The biogas calorific value is typically in the range of 18-24 MJ/Nm^3.

Most of the biogas produced in the EU is used in combined heat and power generation (CHP) systems mainly based on gas engines (spark ignition or compressed ignition, however, the latter usually in the dual-fuel configuration). In total 61 TWh of electricity were produced from biogas in the EU in 2015 [10]. The highest production was again observed in Germany: 33,073 GWh of electricity and 69,047 TJ of heat, with an installed capacity of 4803 MW. In Spain these values were 982 GWh, 2474 TJ and 224 MW, respectively. Other application involves the use of biogas to produce heat for various purposes by its combustion in boilers and other appliances [13]. Also, CHP systems using gas turbines are sometimes applied.

Electricity produced in CHP plants based on biogas generation can be used for covering the auxiliary power of the systems and the needs of local industry, it can also be sold to the grid if the needs are lower than production. The same applies to heat. Nevertheless, the CHP systems fed with post-fermentation gas are often characterised by very good profitability rates, which is mainly due to favourable economic conditions (such as avoidance of the purchase of electricity from the grid and financial incentives).

Biomethane production is becoming more and more attractive because it increases the range of potential use of gas. An interesting document presenting the main technologies, needs, costs and challenges (technical, economic and political) connected to the implementation of these technologies has been published by the Spanish gas company Naturgy [19], which also in 2018 launched a project aiming at a production of biomethane with the use of anaerobic digestion and renewable hydrogen [20]. The biggest challenge regarding implementation on a large scale of biogas and biomethane use is economic profitability of their production. At present, although it significantly depends on the size of the system and type of biomass used as a feedstock, this cost is in general too high to compete with traditional technologies based on natural gas, unless the production is subsidised. According to the studies presented in [21], cost of biomethane is around 46 €/MWh and would need a subsidy of 22 €/MWh to become competitive. Another studies [4] show the cost of biomethane at 0.76 €/m^3 for biomass cost at 27 €/t, which is significantly higher than price of natural gas. Authors in [22] provide an economic and environmental analysis regarding biogas and biomethane plants for several typologies of animal residues in Italy. They conclude that economic viability depends to a large extent on the size of a plant and types of residues; however, they indicate subsidies as having a key-role in economic analysis.

Although the main sources of biogas are sewage treatment plants and landfills, manure-based biogas production has also gained attention, since its potential as a waste-to-energy solution is quite significant. According to [12], livestock and poultry population in the EU amounts to 1,894,821 thousands of heads, with the highest number in France (327,324 thousands of heads), Spain (231,598 thousands of heads), United Kingdom (204,067 thousands of heads), Italy (181,841 thousands of heads) and Poland (176,681 thousands of heads). The biogas potential in the EU amounts to 25,727 million m^3 CH_4 theoretically and 16,081 million m^3 CH_4 realistically, which can contribute to the substitution of 3% of natural gas consumption. For Spain biogas potential is estimated at 2298 million m^3 CH_4 (theoretically) and 1653 million m^3 CH_4 (realistically), which constitutes almost 5% of the use of natural gas [12].

Spain has a significant potential for the use of manure in energy generation. This is confirmed by the study presented in [12] showing two scenarios of biomass collection. The first assumes optimal location of plants considering a fixed collection area and setting the plant capacity depending on local resource availability. The second takes into account optimal location of plants of certain capacities and establishes the area required to supply the feedstock to the plant considering a maximum radius of 10 km. In both scenarios the estimated total capacity for Spain is one of the highest in Europe, amounting to 648.4 MW in one scenario and 559.0 MW in the other, with the expectations for the EU at 6637.9 MW and 5720.8 MW, respectively [12]. Thus, the potential use of manure for energy generation and biogas for distributed power generation based on medium to large scale generation technologies, such as gas engines and gas turbines, is high.

Within this context, the goal of the present study is to holistically asses two cases based on manure fermentation for the production of useful products, i.e. biomethane (through biogas upgrading) and energy (biogas combustion in a gas engine to produce electricity and heat). While the available literature in this field usually focuses on the detailed analysis of environmental and/or economic impacts (e.g. [23][24]), this article aims to consistently address technical, economic and environmental aspects of this type of energy system in Spain. Hence, the novelty of the study lies in the cross-cutting evaluation of the proposed solutions robustly combining thermodynamic, economic and environmental aspects.

2. Material and methods

2.1 Description of the analysed cases

This paper addresses a comprehensive assessment of two systems based on manure fermentation. In a typical configuration for biogas generation, animal manure is collected and fed to the reactor, where it stays for a determined period of time, depending on the feedstock and needs. The produced biogas is collected and has to be cleaned in order to comply with both environmental laws and the requirements of the components of the system in which it is used or gas network. Solid residues are removed at the end of the fermentation process and can be used, e.g. as a fertiliser according to the Spanish Royal Decree 506/2013. Biogas can serve for the generation of electricity and/or heat generation, employing available technologies.

Here two cases were studied in detail. The first variant (Case 1) involves the production of biogas in manure fermentation, its upgrading (cleaning and removal of CO_2 from the gas) and injection to the grid. The second variant (Case 2) assumes combustion of the biogas in a gas engine to produce electricity and heat that can be used locally and/or sold to the grid. The analysis is made for the Spanish market, for which such solutions are very promising. The goal of this study is to jointly evaluate the thermodynamic, economic and environmental performance of these two systems. For this purpose, a detailed model of both cases was built. Thermodynamic analysis was followed by economic analysis, made with the use of discounted methods, and environmental analysis using Life Cycle Assessment (LCA), a well-established methodology to evaluate the environmental aspects and potential impacts [25,26].

To achieve the goal of this study, the detailed simulation models of the proposed systems were built by means of the process simulation software Aspen Plus [27] and a Visual Basic for Applications (VBA) tool in MS Excel. For the calculations of thermodynamic parameters, built-in Aspen Plus methods were used, i.e. Peng-Robinson [28] and ELECNRTL [29]. In the first step, thermodynamic analysis was performed and material and energy flows were calculated in all the most important points of the systems. The outputs from the analysis served as the input for the economic analysis and the LCA. Economic analysis was made in the in-house spreadsheet tool and LCA was conducted using SimaPro.

2.1.1. Case 1

Case 1 assumes production of CH_4-rich gas with the required composition for its introduction in the Spanish gas grid. For both cases manure fermentation was considered. It was assumed that a desulphurisation step is present in both cases, even though it is mainly needed in Case 1 to fulfil the requirements of the CO_2 capture process and the gas network.

The detailed model of the systems was built in Aspen Plus software and is shown in Fig. 1. In both cases, manure is mixed with water and enters the anaerobic digester, operating at 40°C and 1.6 bar, where it is converted into biogas. For the calculation of the biogas composition, the Buswell equation was used. In general, it is an equation often used in anaerobic systems modelling for the calculations of breakdown of a generic organic material of chemical composition $C_cH_hO_oN_nS_s$ into CH_4, CO_2, NH_3 and H_2S [30-32].

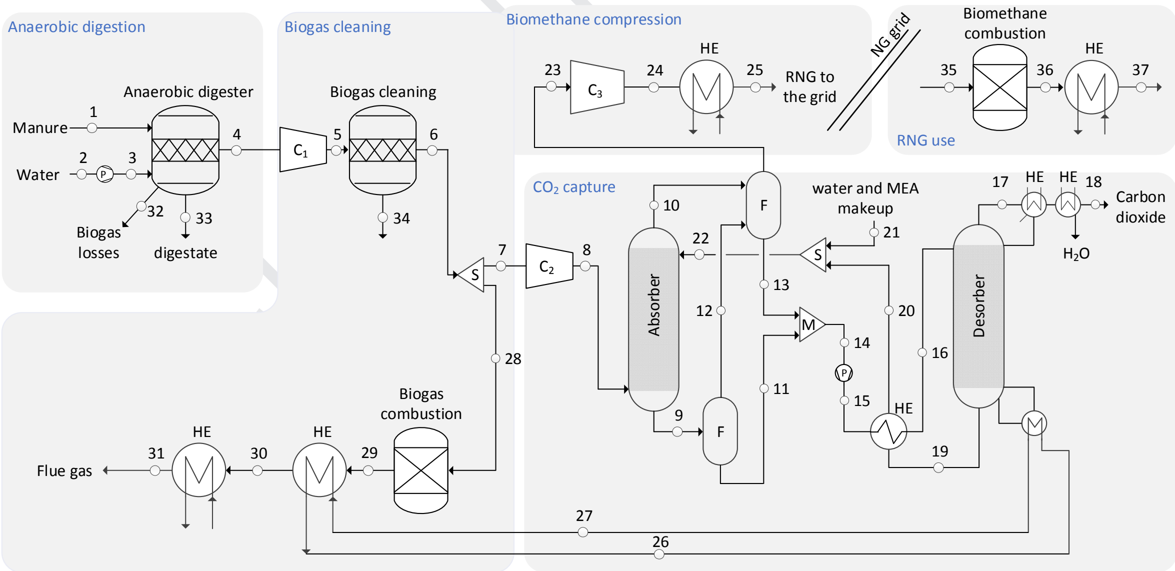

Fig. 1. Scheme of the system with manure fermentation and biomass upgrading (Case 1).

The produced biogas (point 4) is collected and has to be cleaned. Here it was considered that desulphurisation is conducted in order to prevent formation of sulphur oxides during combustion and formation of corrosive sulphur compounds in the carbon capture process. Before entering the reactor, the stream is compressed to 2.1 bar. Desulphurisation and removal of hydrochloric acid proceeds with the use of 5% $FeCl_2$ and 1% $Ca(OH)_2$ water solution, according to the reactions:

$$FeCl_2 + H_2S \rightarrow 2\,HCl + FeS \tag{1}$$

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O \tag{2}$$

Until this step, both cases are treated exactly in the same way. However, the subsequent treatment is different. In Case 1, purified biogas is compressed to the pressure required in the CO_2 capture process and is split into two streams. One part is directed to combustion to generate the heat required for CO_2 desorption. The biogas that undergoes carbon dioxide capture is introduced in the absorber, operating at 3.4 bar. A methane-rich stream (10) is flashed in order to remove water and then fleshed again, together with the CH_4-rich stream (12). The resulting stream (23) is compressed to the pressure required by the gas network in a 2-section compressor (C_3) with intersection cooling to 50°C. Carbon dioxide is removed in an absorption process based on the use of MEA solution, according to the reactions presented in [33]. The absorber consists of 6 stages and a stripper of 8 stages. Both columns were modelled as equilibrium columns and the absorption process was adiabatic. The construction parameters of the columns were not taken into account in the analyses.

In the capture process, significant amount of heat is required in the desorption process. It was assumed that this heat is generated within the system through the combustion of part of the biogas (28) in the combustion chamber. The stream of biogas is calculated to satisfy the need of the stripper. The whole CO_2 capture process was designed to obtain a stream of upgraded biogas that fulfils the requirements of the grid as presented in [34]. Finally, the main assumptions for thermodynamic calculations of Case 1 are summarised in Table 1.

Table 1. Main assumptions for the analysis of Case 1.

Parameter	**Unit**	**Value**
Manure flow	kg/h	21,350.4
Pressure in the anaerobic digester	bar	1.6
Temperature in the anaerobic digester	°C	42
Biogas losses in fermentation	%	2
Temperature in the desulphurisation reactor	°C	30
Absorber pressure	bar	3.4
Stripper pressure	bar	3.5
CH_4 content required in gas injected to the grid	%	>95
CO_2 content required in gas injected to the grid	%	<2
Pressure of gas injected to the grid	bar	15

2.2.2. Case 2

Case 2 (Fig. 2) involves the production and cleaning (desulphurisation before combustion in gas engine decreases the emissions of sulphur oxides to the atmosphere, thus reducing environmental effects) of biogas, which is modelled in the same way as in Case 1 and generation of electricity and heat in CHP. Here, a gas piston engine was assumed. After cleaning, biogas (point 7) is mixed with air to form a combustible gas mixture (9), compressed in a turbocharger and fed to the piston engine (10). High-temperature heat from the exhaust gas is used for heating the water in a heat exchanger (HR). Low-temperature heat comes from cooling the turbocharger's intercooler, water jacket and oil sump. Part of this heat, depending on the process type, can be used for the needs of the process itself (e.g., to heat up the reactors). In this analysis, the characteristics of the gas engine, such as efficiencies and exhaust gas temperature were based on the AB ECOMAX Biogas engine line [35]. The model of anaerobic digester and desulphurisation reactor was built in Aspen Plus while gas engine calculations were made with the use of VBA in MS Excel, based on the models that have been developed earlier by the authors (e.g., [36-37]). The main assumptions for thermodynamic calculations of Case 2 are summarised in Table 2.

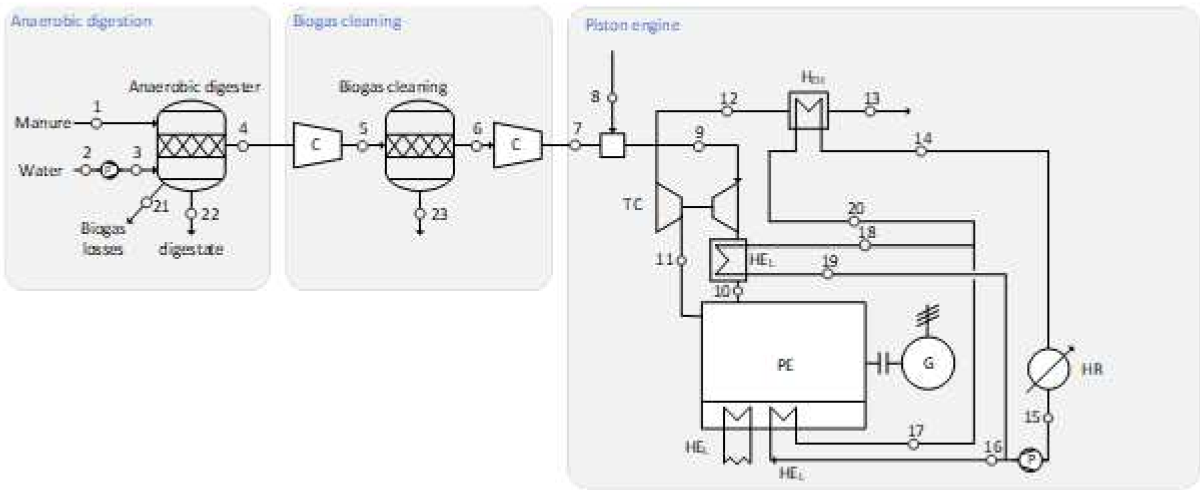

Fig. 2. Scheme of the system with the use of biogas in CHP (Case 2).

Table 2. Main assumptions for the analysis of Case 2.

Parameter	Unit	Value
Manure flow	kg/h	21,350.4
Pressure in the anaerobic digester	bar	1.6
Temperature in the anaerobic digester	°C	42
Biogas losses in fermentation	%	2
Temperature in the desulphurisation reactor	°C	30
Electricity generation efficiency	%	41.6
Heat generation efficiency	%	41.5
Overall efficiency of gas engine	%	83.1
Temperature characteristic of the DH network (supply/return)	°C	90/70

2.2. Main assumptions for economic analysis

For the analysed cases an economic analysis was carried out using the NPV (Net Present Value) discount method, considering the guidelines presented in [38], and determined based on the following equation:

$$NPV=\sum_{t=0}^{t=N}\frac{CF_t}{(1+r)^t}\,. \tag{3}$$

In this equation, r is the discount rate, and t represents consecutive years from the beginning of the investment. The cash flows (CF) are determined from the following equation:

$$CF_t = [-J + S - (C_{op} + T_{in} + C_{wc}) + A + L]_t \,, \tag{4}$$

where J represents the investment costs, S is the revenue from sales, C_{op} represents the operating costs, T_{in} is the income tax, C_{wc} denotes the change in the working capital, A is the depreciation, and L stands for the salvage value.

By setting the net present value to zero (NPV = 0), a break-even price of the production of products, e.g. electricity or biomethane, can be determined. This price, also known as levelised cost, is the minimum sale price for the produced renewable gas that ensures profitability of the investment after a determined period of time.

The analysis assumes that both cases under evaluation operate 8000 h per year and the lifetime of the installations is 20 years. Capital investments (CAPEX) were estimated based on literature data, e.g. [4,9,39,47], and when needed the technologies were scaled to the size of the installations analysed in this paper, or the unit investment costs index was used (e.g., [39,41,48]). The values were updated to the year 2018 using CEPCI (Chemical Engineering Plant Cost Index) [42]. The most important assumptions for economic analysis are presented in Table 3.

Table 3. Main assumptions for the economic analysis of the selected technologies.

Parameter	Unit	Value
Annual working time	h	8000
Exploitation time	years	20
Construction time	years	1
Share of own means	%	50
Share of commercial credit	%	50
Discount rate	%	5
Loan interest rate	%	8
Repayment period	years	10
Income tax	%	25
Nominal price of manure	€/GJ	7.5
Price of MEA	€/t	1000
Price of water	€/m^3	1.1
Price of electricity from grid	€/MWh	60.6
Cost of personnel	€/month	4000
Number of personnel	persons	2
Cost of insurance	%CAPEX/month	2.0
Property tax	%CAPEX/year	1.0
Cost of repairs and maintenance	%CAPEX	3.0
Other operational costs	%CAPEX/year	0.01

2.3. LCA framework

For environmental analysis purposes, the core function of the systems evaluated is defined as the management of the manure. In LCA studies, the functional unit (FU) quantifies the function of the system and provides a reference unit [25]. In both variants, the FU of the LCA was defined as the management of 1 kg of manure. A schematic outline of the systems and the boundaries that are set for the LCA study is presented in Fig. 3 and Fig. 4 for Case 1 and Case 2, respectively. System boundaries determine the unit processes included in the evaluated system [25]. In this sense, the whole conversion process of biogas from manure to electricity and/or heat was considered. According to the main function of the cases and in order to avoid allocation, an avoided burdens approach was followed: the outputs of each case (electricity and/or heat) substitute the production mix of the corresponding type of conventional energy (Spanish grid electricity and/or heat from natural gas). Capital goods and digestate management in both variants were excluded from the analysis. Further details on the LCA study are available in Section 3.3.

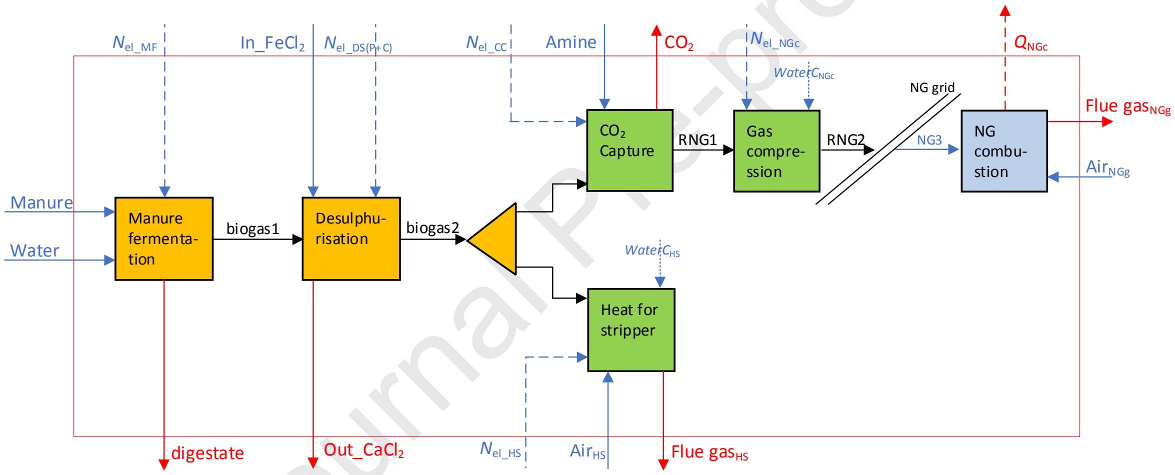

Fig. 3. Schematic diagram of Case 1.

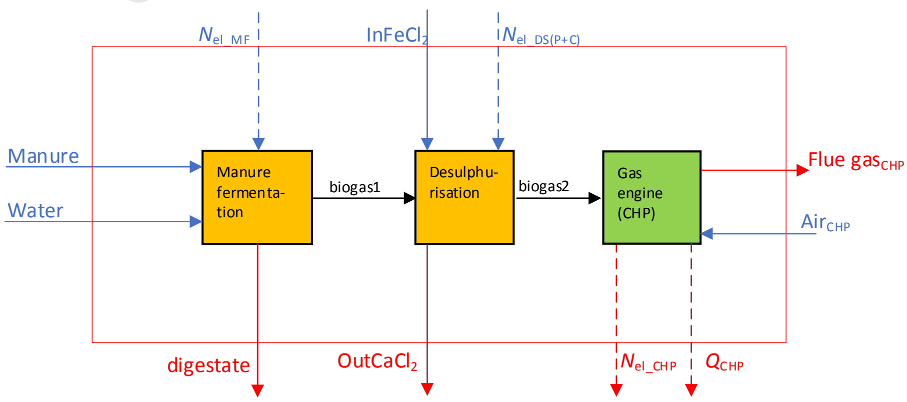

Fig. 4. Schematic diagram of Case 2.

3. Results and discussion

3.1. Results of thermodynamic assessment

The analysed cases are characterised by different outputs (mass and energy streams), thus they cannot be directly compared. The main goal of the operation of Case 1 is to produce a stream of gas rich in methane that fulfils the requirements of the gas grid. As a result, the high-quality product obtained can be used to satisfy the demand for electricity and heat at any end-user connected to the grid whenever it is needed, as gas grid plays the role of energy storage. This gives higher flexibility than Case 2, which assumes generation of energy when biogas is available. The advantage of this second solution is that biogas does not have to be upgraded as it has a composition suitable for combustion in gas engine. Thus, the whole value chain is significantly shorter and less complex than in Case 1.

For the thermodynamic analysis, the auxiliary power and heat required for the process were calculated as well as the heat and electricity streams generated within the systems' boundaries. Furthermore, the composition of streams in all the most important points of the systems was determined. Main results for both cases are presented in Table 4. Unit heat and electricity required in the processes are defined as the amount of heat or electricity that is used in the process related to the stream of product, expressed in mass flow units (kg/s). Purity is a molar share of a given compound in the outlet stream while recovery rate is the ratio of mass stream of a considered compound at the exit to the mass stream of this compound at the inlet to the system.

Table 4. Main results from the thermodynamic analysis of the systems.

Parameter	**Unit**	**Value**
Biogas stream (after cleaning)	kg/h	6611.8
Biogas lower heating value	MJ/kg	12.44
Biogas composition after fermentation	-	
H_2O		0.0483
CH_4		0.4585
CO_2		0.4586
NH_3		0.0010
H_2S		0.0000
Biogas composition after desulphurisation	-	
H_2O		0.0277
CH_4		0.4681
CO_2		0.5042
NH_3		0.0000
H_2S		0.0000
CASE 1		
Share of biogas directed to CO_2 capture in total stream of generated biogas	-	0.7290
Total heat required for CO_2 separation	kW	4453.4
Unit heat required for CO_2 separation	kJ/kg	5659.15
CO_2 purity (after separation)	-	0.9788
CH_4 recovery rate	-	0.9832
Biomethane directed to the gas grid	kg/h	1242

Biomethane LHV	kJ/kg	47344.3
Composition of gas directed to gas grid (molar basis)	-	
CH_4		0.9795
CO_2		0.0200
H_2O		0.0005
Auxiliary electric power of the process	kW	250.2
Unit electricity required for generation of CH_4-rich stream	kJ/kg_{CH4}	764.35
Unit heat required for generation of CH_4-rich stream	kJ/kg_{CH4}	13605.20
CASE 2		
Chemical energy of fuel supplied to gas engine	kW	22858.2
Electricity production in gas engine	kW	9508.0
Low-temperature heat generation in gas engine	kW	5194.6
High-temperature heat generation in gas engine	kW	5284.9
Total heat produced in gas engine	kW	10479.5
Auxiliary power of the system	kW	373.0

The main advantage of Case 1 is the production of a gas with high CH_4 content (here almost 98% share). On the other hand, significant amount of heat is required to perform the CO_2 capture process, which is provided by burning part of the produced biogas (27.1% mass base). In Case 2, biogas does not have to be upgraded as its composition allows its direct use in gas engines. For the assumptions made here, 9.5 MW of electric power can be achieved. This electricity can cover auxiliary power of the system, can be used locally (to avoid purchase of electricity) and/or can be sold to the grid. The operation of the gas engine depends on the availability of biogas. In both cases significant amount of heat is produced (e.g. from intersectional cooling of compressors or cooling of gases) that can be potentially utilised (e.g. for district heating purposes); however, this heat is mainly low quality, thus its use may be limited.

One of the main thermodynamic indicators of the systems is their efficiency. It is very important to define the efficiency properly, especially if it should serve for a comparison of two technologies. When the systems being compared have different outputs (as in this work, the output for Case 1 is biomethane and for Case 2 is electricity and heat), the boundaries of the systems should be carefully considered. The efficiency of Case 1 (η_{C1}) and Case 2 (η_{C2}) is thus calculated according to the following general formulas:

$$\eta_{\mathrm{C1}} = \eta_{\mathrm{AD}} \cdot \eta_{\mathrm{CC}} \cdot \eta_{\mathrm{BC}} \tag{3}$$

$$\eta_{C2} = \eta_{\mathrm{AD}} \cdot \eta_{\mathrm{PE}} \tag{4}$$

where η_{AD} is the efficiency of anaerobic digestion, η_{CC} is the efficiency of carbon dioxide capture, η_{BC} is the efficiency of biomethane combustion in terminal technology, and η_{PE} stands for the overall efficiency of the piston engine.

Here it was assumed that conversion of biomass to biogas is not considered and that efficiency of anaerobic digestion results only from biogas losses (3%); thus, it is equal to 0.97 in Eqs. 3 and 4). The efficiency of Case 1, calculated as the chemical energy of the produced gas related to the chemical energy of the raw biogas is equal to 71.68%, while if calculated according to Eq. (3) is 68.10%. This results mainly from the fact that part of biogas is burned to provide heat to the desorption process. The efficiency of Case 2 can be described as the overall efficiency of gas engine, which is equal to 83.1%. Thus, it can be concluded that Case 2 has more favourable thermodynamic characteristics than Case 1.

3.2. Results of economic analysis

The results of the thermodynamic analysis of the systems served as input values for their economic evaluation. Table 5 presents the estimation of the capital expenditure for both cases considered here.

Table 5. Investment costs for the analysed technologies.

Installation	Cost, $€_{2018}$	
	Case 1	Case 2
Manure fermentation	5 629 501	5 629 501
Biogas cleaning	1 125 900	1 125 900
CO_2 capture	1 129 500	-
Heat for scrubbing	579 724	-
Biomethane compression	231 335	-
Piston engine	-	4 960 940
High temperature heat recovery		868 469
Other unlisted[1]	869 596	1 258 481
CAPEX (Total)	9 565 557	13 843 291

[1] Assumed 10% of total investment

Since the systems are characterised by different products, i.e., in Case 1 biomethane (RNG) and in Case 2 electricity, it was decided to calculate the break-even price of biomethane ($c_{RNG}^{b\text{-}e}$) and electricity ($c_{el}^{b\text{-}e}$), respectively. The results are presented in Table 6.

Table 6. Break-even price of products for the analysed cases.

Item	€/GJ	€/MWh
Price of RNG (Case 1)	16.77	60.36
Price of electricity (Case 2)	28.92	104.10

Break-even price of electricity in Case 2 is similar to the current price for non-household consumers (medium size) in Spain, which is 0.1092 €/kWh **Error! Reference source not found.**. The final economic assessment results depend on the assumptions made and their quality. The economic profitability of a system is affected by many factors, including mainly the investment cost associated with the individual machines and equipment, operation costs, such as the price of feedstock, the price of the final products, e.g. heat and electricity, fuel, and the existing support mechanisms. A change of even one of these values may significantly bias the viability of the investment. Influence of such a change is usually assessed with the use of sensitivity analysis, which helps identify bottlenecks and draw conclusions in order to improve the profitability of the investment. For the cases presented in this work, the influence of the price of biomass and annual working time were identified to have the highest influence on the results [39,40]. Thus, the influence of these two quantities on the break-even price of products was analysed. The results are presented in Figs. 5 and 6.

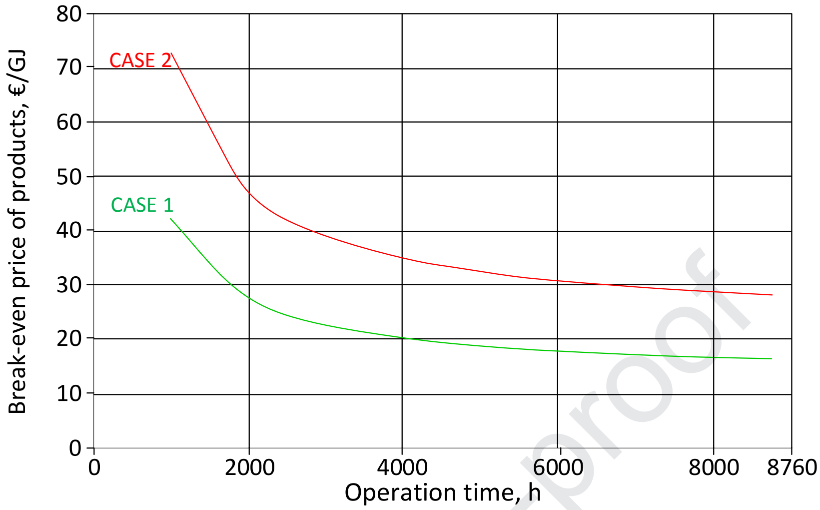

Fig. 5. Influence of the operation time on the break-even price of biomethane (Case 1) and electricity (Case 2).

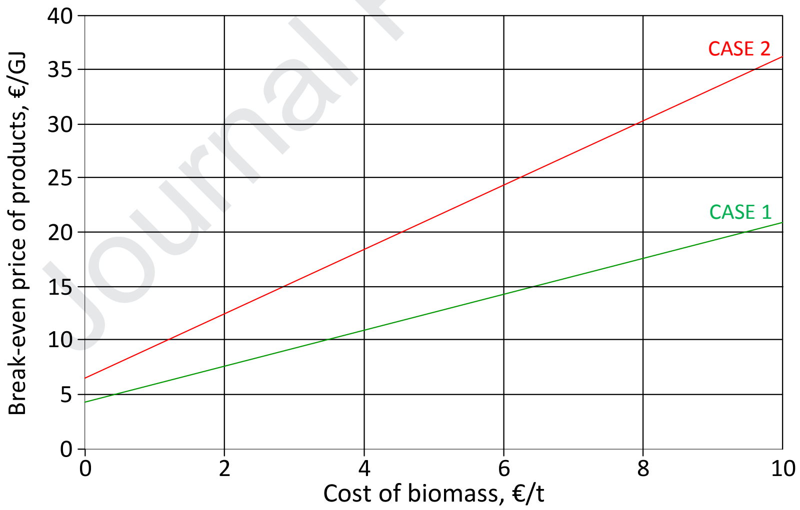

Fig. 6. Influence of the price of biomass on the break-even price of biomethane (Case 1) and electricity (Case 2).

Economic viability of the systems strongly depends on all the analysed parameters. An operation time below 4000 h per year significantly influences the break-even price of products. On the other hand, if the cost of biomass can be decreased, in the most optimistic scenario if the feedstock can be obtained for free, the break-even price of products would be 4.29 €/GJ and 6.55 €/GJ for Case 1 and Case 2, respectively.

It has to be underlined that many more parameters may influence the final results including economic indicators (e.g., capital investment, assumed discount rate, tax rate, method of funding, costs of utilities, economic incentives) and technical indicators (e.g., efficiencies of the devices and processes).

3.3. LCA results

The results of the thermodynamic analysis provided the input data for the environmental analysis of the systems. Tables 7 and 8 present the main inventory data of Cases 1 and 2, respectively. The process simulation previously detailed was used as the main source of foreground data for both variants. Data for background processes were taken from the ecoinvent database [50]. As explained in Section 2.3, the function of both systems refers to the management of 1 kg of manure while avoided products were considered in Tables 7 and 8 according to the system expansion approach followed. Carbon dioxide and methane emissions were also included as key outputs in these inventory tables. Based on the type of feedstock used, these emissions were considered biogenic. It should be noted that the methane emissions are mainly due to biogas leakage in the anaerobic digestion plant [51].

Table 7. Main inventory data of Case 1 referred to the management of 1 kg of manure.

INPUTS			OUPUTS		
From the technosphere			**To the technosphere**		
Manure	1.00	kg	*Avoided products*		
			Heat from combustion of natural gas in industrial furnace	1.52	MJ
Iron (II) chloride	$3.44 \cdot 10^{-2}$	kg	*Waste to treatment*		
Calcium hydroxide	$6.38 \cdot 10^{-3}$	kg	Waste to landfill	$3.35 \cdot 10^{-2}$	kg
MEA	$4.15 \cdot 10^{-4}$	kg			
Electricity	$1.93 \cdot 10^{-2}$	kWh			
From the environment			**To the environment**		
Water	1.00	kg	*Emissions to the air*		
Air	1.36	kg	H_2O	0.17	kg
			Biogenic CO_2	0.40	kg
			Biogenic CH_4	$1.36 \cdot 10^{-2}$	kg
			MEA	$2.43 \cdot 10^{-4}$	kg
			O_2	$1.90 \cdot 10^{-2}$	kg
			N_2	1.04	kg

Table 8. Main inventory data of Case 2 referred to the management of 1 kg of manure.

INPUTS			OUPUTS		
From the technosphere			**To the technosphere**		
Manure	1.00	kg	*Avoided products*		
Iron (II) chloride	$3.44 \cdot 10^{-2}$	kg	Electricity mix ES	0.42	kWh
Calcium hydroxide	$6.38 \cdot 10^{-3}$	kg	Heat from combustion of natural gas in industrial furnace	1.73	MJ
			Waste to treatment		
			Waste to landfill	$3.35 \cdot 10^{-2}$	kg

From the environment			**To the environment**		
Water	1.00	kg	*Emissions to the air*		
Air	1.68	kg	H_2O	0.79	kg
			Biogenic CO_2	0.13	kg
			Biogenic CH_4	$1.22 \cdot 10^{-2}$	kg
			O_2	$5.25 \cdot 10^{-2}$	kg
			N_2	0.90	kg

Within the LCA methodology, the Life Cycle Impact Assessment (LCIA) step associates the inventory data collected with different environmental impact categories and their corresponding indicators. The environmental characterisation of both cases was carried out through the implementation of the Life Cycle Inventories (LCIs) in SimaPro [51]. The life-cycle profile was characterised by two impact categories: global warming impact potential (GWP; carbon footprint) and cumulative non-renewable energy demand (CED; non-renewable energy footprint). GWP was evaluated according to IPCC [52] while CED (fossil plus nuclear) was quantified according to VDI guidelines [53]. The rationale behind this selection is motivated by the fact that these life-cycle indicators are among the most common and relevant ones for assessing manure-based biogas production systems in LCA studies according to [54]. Fig. 7 shows the comparison of both cases in terms of carbon and energy footprint.

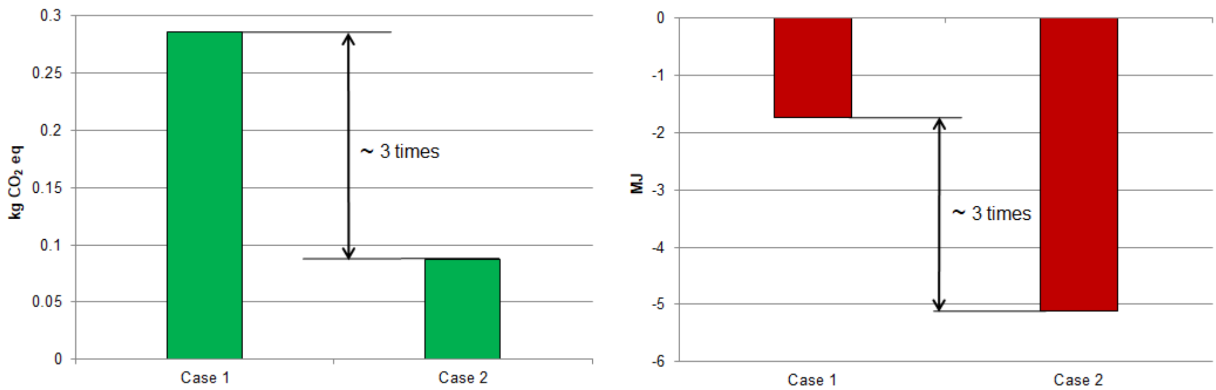

Fig. 7. Carbon footprint and energy footprint of Cases 1 and 2.

As observed, the system with the use of biogas in CHP presents the best environmental profile in the two categories evaluated, improving around three times Case 1. Methane losses, especially those located in the anaerobic digester, were found to be mainly responsible for the carbon footprint. Despite this fact, it should be highlighted the suitable energy footprint of both cases, closely linked to the avoided production of conventional electricity and/or heat.

Finally, the sensitivity of the carbon footprint results to (i) the percentage of biogas losses in fermentation and (ii) the consideration or not of CO_2 and CH_4 emissions as biogenic was explored. Regarding the first point, when assuming no biogas losses, the carbon footprint of Case 1 shows a 63% reduction and that of Case 2 reaches a favourable value of -0.08 kg CO_2 eq/FU (thus emphasising the role of the system expansion approach). On the other hand, the assumption of an increased percentage of biogas losses (5%) would lead to double and quadruple the carbon footprint of Cases 1 and 2, respectively. Concerning the second point, if CO_2 and CH_4 emissions are not considered biogenic, then the carbon footprint of Cases 1 and 2 would be 2.5 and 3 times higher than the original results, respectively. Even though the preference of Case 2 over Case 1 was found not to be affected by the sensitivity analysis, the discussed carbon footprint results highlight the importance of the role of the analyst in making appropriate methodological and modelling choices.

4. Conclusions

This paper holistically addressed different ways of using biogas from manure fermentation. Two variants were analysed: Case 1 involving production of biogas from manure fermentation, its upgrading and injection to the grid, and Case 2, involving combustion of the biogas in a gas engine to produce electricity and heat. From the point of view of thermodynamic assessment, Case 2 is characterised by higher overall efficiency (involving production of electricity and heat). However, it has to be underlined that although in both cases the input (chemical energy of biomass) is similar, the outputs (biomethane and electricity) are different, thus comparison of only efficiencies is not sufficient.

The economic analysis showed that the investment costs for the systems of the same size in terms of the use of chemical energy of biomass are higher for Case 2. However, profitability of both systems strongly depends on the assumptions made, especially concerning price of biomass and annual operation time. Thus, such systems can be competitive to other forms of generation, especially if they can cover local demand. Moreover, in case there is a need for heat (for hot water, heating or industrial purposes), systems with gas engines will be even more justified.

From an environmental perspective, a more favourable life-cycle performance was concluded for the use of manure-based biogas for cogeneration, with around three times higher energy savings and lower greenhouse gas emissions than those for the biogas upgrading variant. Future direction of research will include some other technologies that can potentially have better thermodynamic, economic and environmental characteristics.

Nevertheless, it can be concluded that the analysed technologies have potential to produce high-value products based on low-quality biomass. Biomethane may in the future substitute fossil-based natural gas in order to continue using gas-based technologies for electricity and heat generation (not only piston engines, but also gas turbines or combined cycles), as these technologies have many advantages, such as high efficiencies and short start-up times. In such, they can complement renewable energy sources and extend the use of existing natural gas-based generation sources.

However, in order to make such systems more competitive, it is important to gain the attention of the stakeholders to overcome the existing barriers (e.g. higher price, little or no incentives for avoiding CO_2 emission when producing biomethane). A discussion on social aspects of the technology is also needed and will be future direction of research, as well as further optimisation of the technologies with respect to various criteria.

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Highlights:

- Two technologies based on manure fermentation were modelled
- Biomethane production by manure-based biogas upgrading was assessed
- Join thermodynamic, economic and environmental assessment of technologies was made
- System with gas engine showed better thermodynamic and environmental characteristics